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FEATURE ARTICLE

Neutrino mass: A gateway to new physics

Hirohisa. A. Tanaka[*]

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The discovery of non-zero neutrino mass and mixing has opened a portal to physics beyond the Standard Model whose implications are only beginning to be understood. The next decade promises critical developments with a program of ambitious experiments that will probe the fundamental nature of neutrino mass and mixing, and provide important clues on the primordial matter-dominance of the universe.

1 Introduction

Among the elementary particles, neutrinos would certainly be a top contender for the title of "most enigmatic". Throughout the history of our study of these particles, neutrinos have repeatedly defied conventional expectations while conforming to some of our wildest speculations, starting with Pauli's "cardinal sin" of invoking the existence of neutrinos to explain apparent violation of momentum conservation in nuclear β-decay, where he lamented "postulating a particle that cannot be detected". Only after harnessing the previously unimaginable forces present in atomic nuclei in the form of thermonuclear weapons and reactors did we possess the means to create sufficiently intense sources of neutrinos to directly verify their existence. Over the following decades, we have added astrophysical neutrino sources, such as the Sun [1–6], comic rays [7, 8], and supernovae [9, 10], and accelerators [11], to our tools for studying and understanding the neutrino. Studies of the Z boson in colliders such as LEP have also determined the number of standard neutrino species to be three [12]. Recently, studies of the cosmos itself, in the form of the cosmic microwave background and the large scale structure of the universe, where primordial neutrinos produced in the Big Bang leave an indelible imprint, have provided a formidable probe on neutrino properties.

The immediate features of the neutrino arise from what they are not. They are not electrically charged, and thus do not participate directly in electromagnetic interactions. Nor are they endowed with "color", the corresponding charge of the strong interaction. This leaves the weak interaction and gravity. Within the Standard Model of elementary particles, neutrinos are then particularly simple particles. As part of a weak isodoublet in which they are paired with a charged lepton ($e^{\mp}$, $\mu^{\mp}$, $\tau^{\mp}$), their interaction via the weak charged current defines three species or "flavors" (ν_e, ν_μ, ν_τ) of neutrinos and their corresponding antiparticles depending on which of the charged leptons emerges. They can also interact via the weak neutral current, a distant relative of the electromagnetic interaction that arises following spontaneous electroweak symmetry breaking. Historically, the Standard Model also left neutrinos bereft of one other property, namely mass. With this further assumption, the properties and behaviour of the neutrino are nearly completely determined.

What then has earned the neutrino such monikers as "mysterious" or "enigmatic"? While ample reason can be found throughout our history of studying neutrinos, we will focus here on a recent development: the discovery that neutrinos do in fact have mass, contrary to the assumptions of the Standard Model. This gives rise to the following issues and possibilities:

- Neutrinos may possess a hermaphroditic property arising from its mass wherein it is its own antiparticle [13]. Susceptibility to this condition, known as "Majorana mass", is unique to the neutrino, as other Standard Model fermions possess charges that forbid this property. Majorana mass also leads to lepton flavor violation.

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[*] Corresponding author E-mail: tanaka@phas.ubc.ca
Institute for Particle Physics and University of British Columbia

- Massive neutrinos have additional properties and parameters. Most obviously, the numerical values for the non-zero masses of the three neutrinos must be specified. Furthermore, quantum mechanics allows the "mixing" of the flavor states (ν_e, ν_μ, ν_τ) and mass states, where the former are linear combinations of the latter (and vice versa). These linear combinations are summarized by a 3 × 3 unitary matrix U whose elements must be specified.

The first confronts directly the nature of neutrino mass, and whether it is of a fundamentally different nature from the other fermions (the charged leptons e, μ, τ, and the quarks). It has been anticipated that neutrino mass in this form would be a harbinger of physics at otherwise inaccessibly high mass scales, and that a generic relationship, fittingly named the "see saw mechanism", relates these high mass scales to the tiny masses of the neutrino [14].

The endowment of neutrinos with masses and mixing parameters is analogous to the situation in quarks, and one may wonder why this is interesting or unusual. As it turns out, these mass and mixing parameters take rather extraordinary values in the case of neutrinos. The masses are known to be smaller by a factor of at least a million relative to the electron, the next lightest fermion. This again hints at an entirely different origin for neutrino masses from the other Standard Model fermions, where masses arise from the coupling of these particles to the Higgs field. There is also the curious possibility that the neutrinos have a mass ordering that differs from the hierarchical pattern observed in the charged leptons and quarks. This question of "mass hierarchy" raises the possibility that in the "inverted' configuration, there are two quasi-degenerate neutrino mass states. Here "normal" or "inverted" hierarchy is defined with respect to the hierarchical spectra of masses observed in the quark sector, and this configuration may be an important clue in understanding how neutrinos and quarks ended up with such different properties.

The mixing we observe in neutrinos is equally fascinating. Whereas the quarks appear to have a largely monogamous relation where the mass and flavor states nearly coincide, the neutrinos appear to be maximally haphazard in this relationship. The mixing exhibits a near-"tri-bimaximal" structure, wherein one of the mass states appears to be nearly equal parts of each flavor state, and the other two are composed of nearly even contributions of ν_μ and ν_τ [15]. It has been postulated that an underlying mathematical structure of unknown origin may be present [16]. As originally postulated by Kobayashi and Maskawa in the quark sector [17], the three-family mixing structure of neutrinos allow for neutrino/antineutrino asymmetries in the form of CP violation (CPV) arising from an irreducible CP-odd complex phase in the mixing matrix. CPV is a necessary condition for explaining the matter-dominated universe we observe today [18]. Currently, the only known source of CPV, that in quarks, is unable to account for this asymmetry, and attention is now turned to the possibility of CPV in neutrinos. In one leading scenario, known as *leptogenesis* [19], the primordial matter dominance of the universe results from CPV decays of the neutrino's heavy Majorana partners in the early universe. Recently, theoretical studies have raised the possibility of connecting CPV in neutrinos directly to this asymmetry [20]. Whether first- or second-hand, understanding neutrino CPV is essential to even qualitatively account for how our universe came to its matter-dominated state.

The freedom to rotate mass and flavor eigenstates with respect to one another ("mixing"), and non-zero masses, via couplings to the Higgs boson, are fully accommodated in the Standard Model. However, it is silent on what values these parameters should take apart from generic considerations (unitarity, etc.). A more fundamental understanding requires physics beyond the Standard Model. The bewildering incongruity in the pattern of masses and mixing observed in neutrinos with respect to the situation in the quark sector and the possibility of an underlying pattern beg for an explanation. Further precision in measuring the mixing parameters, and resolving such issues as whether neutrinos are Majorana particles, whether they exhibit CPV, and whether their masses are in the normal or inverted hierarchy, will be essential clues towards understanding this situation.

In the following, we will visit recent and foreseen developments in neutrino oscillations and neutrinoless double beta decay, where we can expect exciting new developments over the next decade. Concurrently, we continue to investigate whether neutrinos possess even more exotic properties, such as the existence of "sterile" species that do not interact via the Standard Model couplings; this exciting program will not be discussed here. We will also not have the opportunity to describe the important program of direct neutrino mass measurements [21, 22].

2 Neutrino oscillations

The mixing of neutrino flavor and mass(energy) states gives rise to (proper) time-dependent transitions between neutrino flavor states ($\nu_{e,\mu,\tau}$) known as *neutrino oscillations* [23–26]. Since the oscillation frequencies are determined by the mass-splittings of the neutrinos, the observation of oscillations in atmospheric neutrinos in 1998 [27] was the first definitive evidence that neutrino have mass; massless neutrinos do not oscillate. The amplitudes of these oscillations are governed by the elements of the mixing matrix U; the large oscillation effects observed imply that U contains large off-diagonal elements. Since then, neutrino oscillations are the primary means by which neutrino mixing have been studied using the sun, cosmic rays, reactors [28–30], and accelerators [31–36] as sources.

With three neutrinos, U can be described by three rotations parametrized by angles (conventionally called θ_{12}, θ_{13}, and θ_{23}) and a complex, CP-odd phase δ[1]. Whereas neutrino oscillation in vacuum is sensitive only to the magnitude of the mass eigenvalue differences, the passage of neutrinos through matter gives rise to coherent forward scattering effects which induce interference effects that are sensitive to the ordering of these masses [42] . The impact of these "matter effects" on the oscillation probability offer a way to resolve the mass hierarchy.

In "disappearance" measurements, a beam of a nearly pure flavor state (typically $\bar{\nu}_e$ in the case of reactors and $\nu_\mu/\bar{\nu}_\mu$ in the case of accelerators) is prepared and the deficit of this initial flavor, resulting from the neutrinos oscillating to another flavor, at some distance L away is measured as a function of neutrino energy E (where L/E is directly related to the proper time for the neutrino transit). This energy-dependence of the deficit is governed by the mass splitting, while the amplitudes are governed by the mixing parameters. Figure 1 shows some illustrative disappearance data leading to measurements of θ_{12}, θ_{13}, and θ_{23}. In each plot, the ratio of the observed L/E or E to that expected in the absence of oscillation effects is shown, along with the expected behavior based on the extracted oscillation parameters. The observed deficits, indicative of oscillations, are well-described by the oscillation model, and their large magnitudes are indicative of the large mixing between the neutrino flavor and mass parameters, which in turn are reflected in the large mixing angles extracted from these and other measurements: $\theta_{12} = 33.4 \pm 0.8^\circ$, $\theta_{13} = 8.9 \pm 0.4^\circ$, and $\theta_{23} = 45.6 \pm 3.2^\circ$ [43].

In the coming decade, we can expect increasingly precise measurements of θ_{13} from reactor experiments like Daya Bay, RENO [44], and Double-Chooz [45], and θ_{23} from T2K and NOvA [46]. JUNO and RENO-50 may also increase the precision with which θ_{12} is known [47]. Employing the matter effect, the NOvA experiment, in combination with data from T2K (where the effect is smaller due to the shorter distance and lower energy), will provide our first chance at resolving the neutrino mass hierarchy. These experiments will also look for the first indications of CPV in neutrino oscillations, which will manifest as asymmetries in the $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillation probabilities and in the E-dependence of the oscillation probability. A major development towards this end was the observation of $\nu_\mu \to \nu_e$ oscillations in the T2K experiment as shown in Figure 2 on the left [48]. The observation of this channel of oscillation confirmed that all three mixing angles ($\theta_{12,13,23}$) are non-zero, a condition required to effect CPV in the mixing, and was the first explicit observation of the $\nu_\mu \to \nu_e$ oscillation mode with which CPV effects will be studied. The right plots in Figure 2 illustrate how the oscillation probability varies with the unknown CPV phase δ (with $\delta \neq \{0, \pi\}$ resulting in CP-violating asymmetries), as well as the impact of the mass hierarchy. In addition, JUNO and RENO-50 will attempt to resolve the mass hierarchy by the subtle shift in the oscillation pattern from reactor $\bar{\nu}_e$ induced by the interference of the two mass splittings which depends on the hierarchy [49, 50], while Super-Kamiokande [51], PINGU [52], ORCA [53], and INO [54] will probe the matter effects in atmospheric neutrinos.

Even as current experiments collect data towards observing these effects, it is clear that a new generation of experiments collecting much larger statistics will be needed to definitively observe CPV and to precisely measure δ. To this end, two ambitious efforts are planned. In Japan, Hyper-Kamiokande (HK) [55], a one megaton water Cherenkov detector is proposed as a successor to the highly successful Kamiokande and Superk-Kamiokande detectors. HK represents a factor of 25 increase in fiducial volume (560 kt vs. 22.5 kt) relative to the current Super-Kamiokande detector, with commensurate increase in statistical sensitivity to CPV using the existing T2K neutrino beam line. In the USA, the Long Baseline Neutrino Facility (LBNF) [56, 57] will pursue a similar program at higher energies and longer baseline using large scale ($\mathcal{O}(10\text{ kt})$) liquid argon time projection chambers [58] which will provide exquisite resolution of the details of neutrino interactions unseen since the use bubble chambers. Both experiments expect to start taking data in the 2020s, and will play a decisive role in establishing CPV in neutrinos and measuring δ. As large, underground detectors, these detectors also represent the frontier in studies of proton decay, a "smoking gun" signature of the Grand Unification of the strong and electroweak interactions.

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[1] If the neutrino are Majorana particles, there are two additional phases which do not impact neutrino oscillations [40, 41].

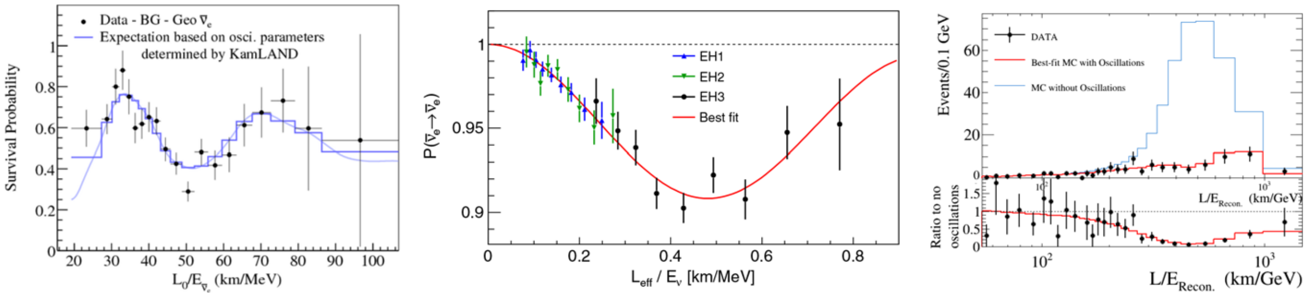

Figure 1 Example neutrino oscillation measurements via disappearance from KamLAND (left, $\bar{\nu}_e$) [37], Daya Bay (center, $\bar{\nu}_e$) [38] and T2K (right, ν_μ) [39] showing the ratio of observed events as a function of L/E or E to the expectation in the absence of neutrino oscillations. The amplitude and period of the oscillation probe the mixing and mass splittings of the neutrino, respectively.

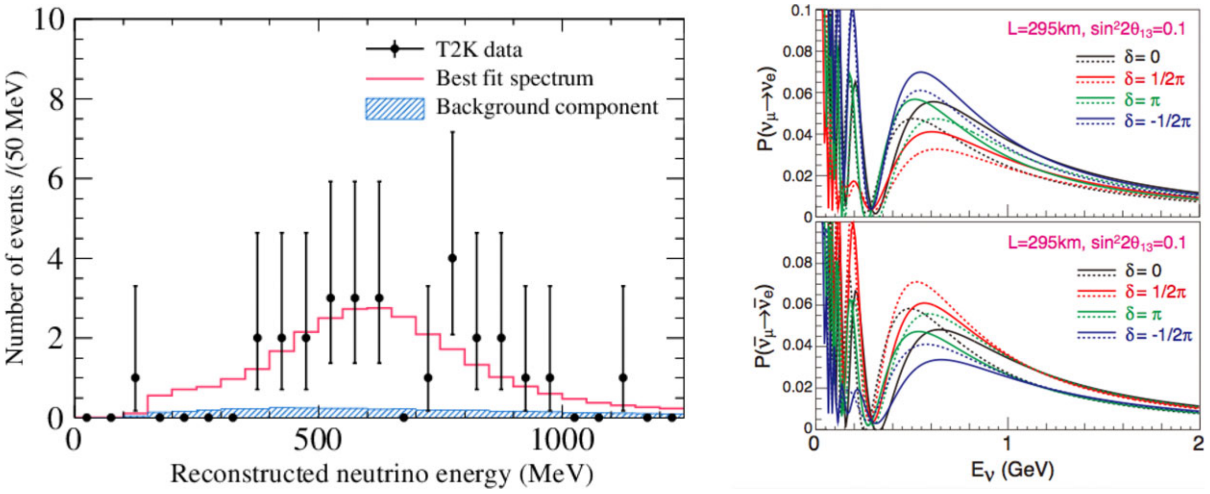

Figure 2 Left: Neutrino energy distribution for $\nu_\mu \to \nu_e$ oscillation candidate events at T2K [48]. The blue hatched distribution shows the expected background, while the red histogram shows the best-fit expectation based on oscillations. Right: $\nu_\mu \to \nu_e$ (top) and $\bar{\nu}_\mu \to \bar{\nu}_e$ (bottom) oscillation probabilties as a function of neutrino energy at $L = 295$ km for different values of the CP-violating phases δ and for normal (solid) and inverted (dashed) hierarchies [55].

They will also be the foremost observatories for neutrinos born in the most extreme processes in the universe, such as supernovae.

3 Neutrinoless double beta decay

The possible Majorana nature of the neutrino leads to processes which violate lepton number by two units, since the mass term couples neutrino (lepton number +1) and antineutrino (-1) states. Currently, the only known means to search for such effects is the so-called neutrinoless double beta decay ("$0\nu 2\beta$") process, in which the effective process $(A, Z) \to 2e^- + (A, Z+2)$ may occur in certain nuclei if the neutrino is in fact a Majorana particle, with a rate which is proportional to $|\langle m_{eff}\rangle|^2 = |\sum_i U_{ei}^2 m_i|^2$. In these isotopes (*e.g.* ^{76}Ge, ^{100}Mo, ^{130}Te, ^{136}Xe), the normal "double beta decay" process, $(A, Z) \to 2e^- + 2\bar{\nu}_e + (A, Z+2)$, can occur even if the neutrino is not Majorana, and thus the $0\nu 2\beta$ process is distinguished by the total energy of the two electrons being at the kinematic endpoint corresponding to the electron pair fully balancing the energy of the recoiling nucleus.

Based on our current estimates of neutrino masses, the allowed range of Majorana masses in relation to m_{min}, the mass of the lightest neutrino, is shown on the left in Figure 3. Two bands are present, corresponding to inverted (IH) and normal (NH) hierarchy, respectively. Towards the right, where the entire mass spectrum is lifted to high values by large values of m_{min}, m_{eff} scales directly with m_{min} and the hierarchy has little impact. To the left, where m_{min} is small, m_{eff} is impacted by whether there are two high mass states corresponding to the inverted

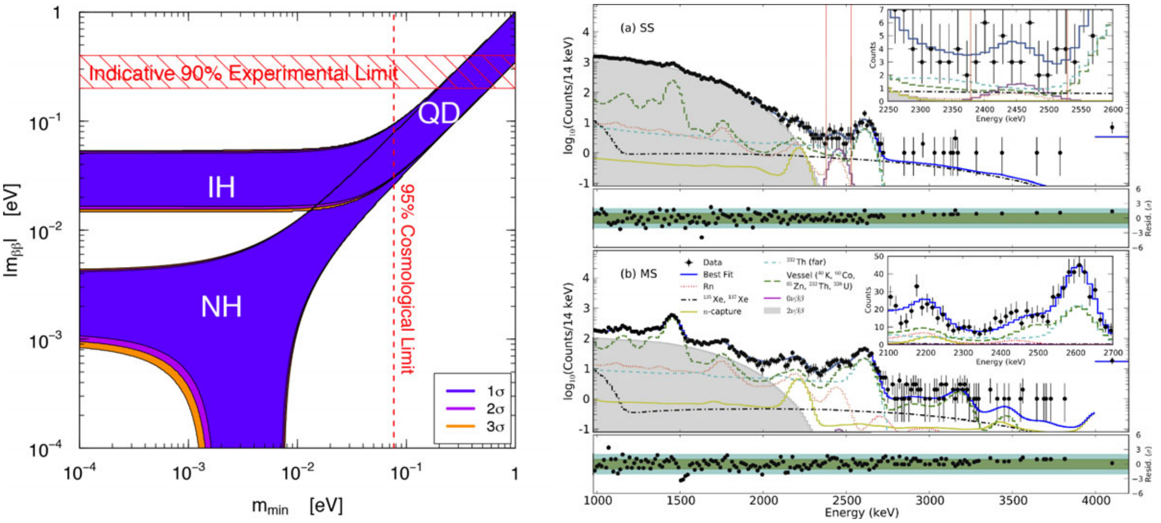

Figure 3 Left: Allowed regions of m_{eff} and m_{min}, the lightest neutrino mass eigensvalue, for normal (NH) and inverted (IH) hierarchies assuming that the neutrino is a Majorana particle [59]. Bounds from $0\nu2\beta$ experiments and cosmological data are also shown. Right: Observed energy spectra from EXO-200 [60] for signal-enriched single site (SS) events (top) and background-enriched multiple site (MS) events (bottom). In addition to backgrounds, the $2\nu2\beta$ contribution and the best fit $0\nu2\beta$ signal are shown in shaded gray and magenta, respectively. The inset shows the $2\nu2\beta$ endpoint region where the $0\nu2\beta$ signal is expected.

case, or only one, as in the normal hierarchy. In the inverted case, the quasi-degenerate pair of higher neutrino mass eigenstates results in a lower limit in m_{eff} (and the rate of $0\nu2\beta$ decay), while in the normal case, the phases present in the mixing matrix may result in a complete cancellation in m_{eff}, resulting in no $0\nu2\beta$ decay, even if neutrinos are in fact Majorana particles.

Some of the challenges of $0\nu2\beta$ experiments are exemplified in the right plot of Figure 3 from the EXO experiment. First is the expected scarceness of the signal process, shown as the solid magenta curve in the top plot, where at the current bounds, one expects several $0\nu2\beta$ decays per 100 kg of isotope per year. To push the frontier of sensitivity, ever larger quantities of $0\nu2\beta$ candidate isotopes must be used. Second are the background processes, primarily from residual radioactivity occurring within the experimental apparatus, and the intrinsically irreducible standard double β decay process, which is separated from the signal process only by the energy. The demands are tremendous in suppressing contamination, deploying the experiments deep underground to shield them from cosmogenic backgrounds, and then in discriminating the signal process from the remaining background. The latter include topological methods, such as those employed by EXO to suppress backgrounds arising from radioactive γ emissions which typically give rise to multiple-site (MS) electron emission, as distinguished from the single-site (SS) emission expected for $0\nu2\beta$, as well as energy resolution, which is the only means to separate $0\nu2\beta$ decays from the standard double β decay of the same isotope. Additional methods, such as directly tagging the daughter nucleus emerging from the $0\nu2\beta$ decay process, are also under development. A final hurdle involves the nuclear physics necessary to connect an observed $0\nu2\beta$ lifetime with m_{eff} via the matrix element for the transition; typically, this results in a factor of ~ 2 uncertainty in deriving bounds on m_{eff} and comparing results from experiments employing different $0\nu2\beta$ candidate isotopes.

Several $0\nu2\beta$ efforts are under way employing various methods such as dissolving the isotope (^{136}Xe in a large volume of scintillator in KamLAND-ZEN), Xe-based time-projection chambers (EXO, NEXT), calorimetry using crystals carrying candidate isotopes (^{76}Ge in GERDA and ^{130}Te in CUORICINO), and foils containing candidate isotopes embedded within tracking and calorimetric detectors (NEMO) [61–65]. In SNO+, the original SNO cavity has been retrofitted to contain ^{130}Te-loaded scintillator [66]. These experiments are typically deploying approximately tens to hundreds of kg of isotope and reaching sensitivities $\mathcal{O}(10^{25})$ years, resulting in upper bounds on m_{eff} of $200 - 500$ meV.

In the near future, a number of efforts are aiming at sensitivity to $m_{eff} \sim \mathcal{O}(10\text{ meV})$, where they should be sensitive to the full range of the inverted hierarchy if neutrinos are indeed Majorana particles. This entails experiments deploying hundreds of kg of isotope. The more ambitious goal of covering large parts of the normal hierarchy, the task of the following generation of $0\nu2\beta$ experiments, will require ton-scale experiments

4 Conclusions

Since its birth in a trepidatious proposition by Pauli and the discovery of many of its unusual properties, neutrinos have firmly established their place within the Standard Model and Cosmology. Neutrino mass has long been speculated to be a gateway to new physics at high mass scales and with its demonstration through neutrino oscillations, further unusual properties of neutrinos in their mixing and mass structure have been observed. We are embarking on a experimental program that may decisively establish whether neutrinos in fact are Majorana particles, and to provide essential measurements to precisely probe the mass and mixing structure of these particles, which may also establish their potentially central role in effecting the matter-dominated universe we see today. If history serves as a guide, nearly one hundred years after Pauli's famous proposal, the neutrino may provide us with answers to some of the fundamental questions facing our understanding of the universe, while unleashing yet more enigmas and paradoxes.

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